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Holographic Optical Tweezers at the Tip of a Needle

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Abstract—Fibre-based optical tweezers typically rely on engineered fibre terminations yielding limited flexibility in number and positioning of trap sites. Here, we demonstrate holographic optical tweezers delivered by a lensless, high-NA multimode fibre with full positioning control of multiple tweezers independently and in all directions.

Keywords—optical tweezers, multimode fibres, digital holography, wavefront shaping

Optical tweezers allow exerting and measuring minuscule forces in a contactless manner and, particularly in the domain of Biophotonics, have become ubiquitous tools for studying the mechanical properties of cells, molecular motors and biomolecules [1]. Conventional systems are usually based on bulk optical components such as high-NA microscope objective lenses to create sharp and aberrations-free foci that produce gradient forces overcoming the radiation pressure, thus achieving stable 3D trapping using a single beam of light. Miniaturised designs using optical fibres have been the object of intense research in the past two decades, aiming at applications spanning from optofluidics chips to minimally-invasive probes capable of taking the study of the mechanics of biological processes deep within living tissue. Such designs rely mostly on single-mode as well as multicore fibres with elaborate fibre terminations and the optical traps are either static or have limited flexibility in terms of positioning the trap sites [2].

We have developed an all-solid, step-index multimode fibre based on compound ‘soft-glasses’ yielding an unprecedented NA exceeding 1 at wavelengths smaller than 600 nm, and 0.96 at 1064 nm. By utilising and further extending the methods of holographic wavefront shaping for controlling light propagation in multimode fibres [3,4], we demonstrate three-dimensional optical trapping and manipulation via a bare, single fibre [5]. Being inherently holographic, our approach allows generating an arbitrary number of optical tweezers, as well as precisely repositioning them independently in all directions (Fig. 1). Surprisingly, the high-NA fibre probe shows a remarkable macro-bending resilience even for radii of curvature up to 5 cm (Fig. 2), which should be sufficient for a

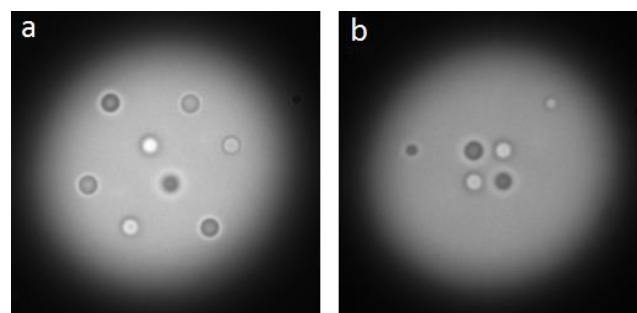


Fig. 1. Dynamic manipulation of holographic optical tweezers delivered through a lensless multimode fibre. Multiple holographic tweezers trapping of (a) eight particles comprising a rotating 3D cube and (b) six particles with different size illustrating Bohr's model of the He atom. The particles appear to have different brightness according to their axial position with respect to the focal plane of the imaging microscope objective (particles appearing ‘brighter’ are at a greater distance from the fibre endface). Incoherent light for illumination is also delivered via the fibre core, which is visible as the blurred disk in the background.

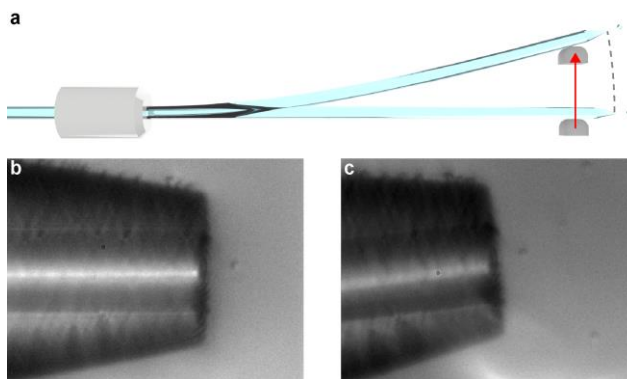


Fig. 2. Resilience of the holographic optical tweezers to bending of the fibre. (a) A static optical trap confining a silica microsphere (1.5 μm diameter) is delivered through a multimode fibre with length 65 mm. The unheld portion of the fibre (15 mm long) is initially straight and is then progressively bent due to the force applied by a motorised stage moving upwards. (b) Side-view image of the trapped particle in the initial, straight conformation of the fibre. (c) Side-view image of the trapped particle in the final, bent conformation of the fibre corresponding to a vertical displacement of 2 mm and a radius of curvature of 5 cm.

broad spectrum of real-world applications. Moreover, the possibility of generating aberration-free foci with NA exceeding 0.8 across the fibre core opens new perspectives for high-resolution holographic micro-endoscopy, paving the way for the delivery of advanced microscopy techniques through air-thin fibre-optic probes.

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